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DETONATION BLAST PRESSURES OF TNT AND C4 AT -100ºC

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14. ABSTRACT

One-lb charges of TNT and C4 were detonated at core temperatures of 30°C and -100ºC, and incident pressure and impulse were compared to determine the effect of cooling on energy release from detonation of the explosive materials. LN2 was used to cool 1-lb (0.45-kg) charges inside two concentric, insulated containers before detonation. Pressure measurements were taken along orthogonal axes 4, 6, 10 and 20 ft from the blast origin. There were no significant statistical differences in incident pressures between shots at ambient temperature and at -100°C, but incident impulse decreased an average of 9.5% for both TNT and C4 at -100°C. The effect on incident impulse decreased with distance from the blast origin, and was too small to mitigate structural damage and injury to personnel. In principle, greater decrease is to be expected at LN2 or liquid helium temperatures, but these will likely be impractical to use in EOD applications.

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This report is published in the interest of scientific and technical information exchange and its publication does not constitute approval or disapproval of its ideas or findings.

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PREFACE

This technical report describes work performed by the Engineering Mechanics Group, Force Protection Branch, Airbase Technologies Division, Materials and Manufacturing Directorate of the Air Force Research Laboratory (AFRL/MLQF) from March 2003 to January 2004, Tyndall Air Force Base, Florida. Support for this project was awarded from the AFRL/ML Laboratory Director's Fund. The group leader was Robert J. Dinan, Civilian, Gov; the principal investigator was John R. Hawk, Contractor, Applied Research Associates; and the project officer was Elizabeth Trawinski, 1st Lt, USAF.

EXECUTIVE SUMMARY

A. Objective

The purpose of this research was to determine the extent to which cryogenic cooling of chemical explosive materials reduces their air blast effects.

B. Background

Any method that could significantly reduce injury to people and damage to buildings and equipment from explosive air blasts would be beneficial to explosive ordnance disposal personnel, whether used in disposal of old or obsolete ordnance or for disruption of improvised explosive devices. Injury and damage from the detonations of conventional chemical high explosives stem primarily from the explosive shock wave pressure and impulse. Therefore, any method that would reduce the shockwave pressure could also make explosive disposal much safer.

Explosive detonation occurs through a very fast but otherwise typical chemical reaction, which generates a pressure wave. As for all chemical reactions, the rate of an explosive detonation should be dependent on temperature. Slowing the rate of reaction should also decrease the intensity of the pressure wave as well as the magnitude of the shockwave pressure and impulse. This series of exploratory experiments were performed as a feasibility determination of the mitigating effect of practically accessible low temperatures on the shockwave pressure and impulse from two common explosives.

C. Scope

TNT and C4 were tested at core temperatures of 85°F (30°C) and −150°F (−100ºC). Incident pressure and impulse were compared to determine what effect cooling had on mitigating the energy release of the explosive materials. Three reference tests were performed for each chemical explosive using 1-lb charges. Three tests were conducted with C4 cooled to −150°F, and two tests were completed with TNT cooled to −150°F.

D. Methods and Procedures

One-lb (0.45-kg) charges of TNT and (separately) C4 were fitted with thermocouples to monitor their core temperatures and then placed inside two concentric, insulated containers, or double coolers. Liquid nitrogen was piped into the inner cooler through a solenoid-operated valve that was cycled by a temperature control unit to maintain −155°F (−105ºC) inside the cooler. The explosive charges were cooled until core temperatures of −155°F were achieved, and then the coolers were moved to a test bed where pressure gauges were set at four different distances along two axes from the blast origin. A temperature rise of 5°F was estimated during transportation of the explosives from the cooling area to the test bed and until detonation. Time histories of incident pressure were

measured and recorded, which allowed comparison of both incident pressure and incident impulse.

E. Results

For TNT and C4, there were no significant statistical differences in incident pressures between the shots at ambient temperature and at –150°F. An average reduction in incident impulse of 9.5% was observed from 4–20 ft from the blast for both TNT and C4. However, the reduction in incident impulse decreased with distance from the blast origin and it appears not to be statistically significant beyond 20 ft.

F. Conclusions

The reduction in incident impulse observed for both TNT and C4 was not sufficient to significantly reduce the potential for considerable damage and injury, and therefore, this technique would be ineffective at reducing the damaging effects of explosive blasts.

G. Recommendations

Similar tests should be conducted at equilibrium cold soaked temperatures in liquid nitrogen (-196°C) and in liquid helium (-268°C) to determine the maximum mitigating effect possible and the temperature threshold for useful mitigation. It is unlikely that such low temperatures can be practically achieved in the field and, until significant reductions in blast pressures and impulses have been observed in field conditions, blast mitigation by cryogenic pretreatment of explosives should not be considered practical.

1.0 Introduction

1.1 Objective

Intuitive arguments, experimental reports and experience with cryogenic processing of ordnance for demilitarization suggest that the blast force of a given charge may be decreased by extreme cooling prior to detonation. This exploratory study was undertaken to examine the effect of cooling to -100ºC (-150ºF)—a condition practically attainable with liquid nitrogen (LN_2) in field situations—on the explosive shock wave pressure and impulse produced by detonation of two common explosives, composition 4 (C4) and 2,4,6-trinitrotoluene (TNT). A practical method of reducing the blast wave pressures and impulses associated with detonations of conventional and improvised high explosives would be valuable to military and civilian explosive ordnance disposal personnel.

1.2 Background

High explosives (HEs) are typically materials containing exactly stoichiometric (*e.g.*, $NH_4NO_2 \rightarrow N_2 + 2\ H_2O$) or near-stoichiometric (*e.g.*, $C_5H_8N_4O_{12} \rightarrow 3\ CO_2 + 2\ CO + 2\ N_2 + 4\ H_2O$) amounts of oxygen to form only thermodynamically stable gaseous products. In comparison with behavior of a typical fuel (HC) that mixes with oxygen or air to burn, this condition of being "premixed" in ideal proportions leaves a relatively small amount of energy (ΔE) available upon complete reaction (*Figure 1*), but it predisposes to very small activation energies ($\Delta E^{\ddagger}$). Thus, HEs are metastable compounds that can react completely within microseconds after initiation.

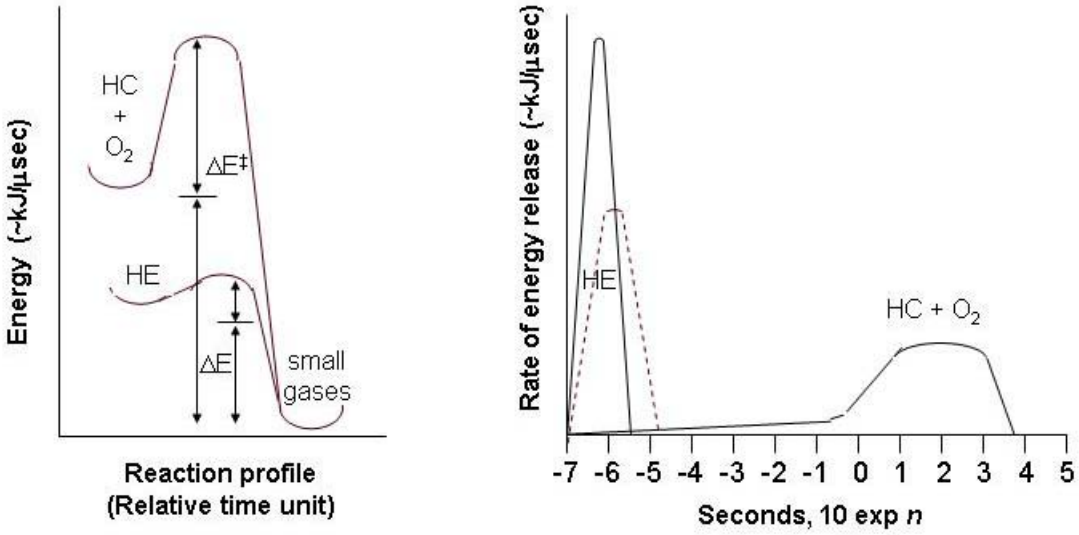

Figure 1. Reactant-to-Product Energy Relationships (left). Time profile of energy release from reaction of ordinary combustion fuels (HC) and high explosives (HE). The dashed curve projects the energy–time profile for HE at ultra low temperature.

Because the activation energy required to initiate decomposition of HEs is greater than zero (*i.e.*, HE can be isolated), it is intuitive to expect that extreme cooling of an HE will decrease both the population of its molecules that have internal energy sufficient to initiate at a given level of activation and the total amount of internal energy available for release. Referring to *Figure 1*, the former effect might be expected to broaden the response on the time axis, and the latter to decrease the area under the curve, both contributing to decrease the blast yield as illustrated by the dashed time–energy profile.

Generations of studies of cryogenic desensitization of initiators, secondary explosives, and propellants have consistently shown[1–3] cooling to –196 °C to cause detectable but unpredictable suppression of sensitivity and occasional inertion of some components and devices containing them, most notably mechanical initiators.[1,2] Workers at Los Alamos found[4] that Comp B was inerted in a LN_2 bath, but that tetryl remained reactive; they also mentioned[4] a decrease in detonation velocity in single tests of Comp C in baths containing Dry Ice–acetone and LN_2, respectively. General Atomics has developed and validated the safety of two commercial processes, cryofracture[5] for production-scale demilitarization of chemical munitions and cryogenic washout[6] of propellants from solid rocket motors (SRMs). In cryofracture, unfuzed chemical-filled rounds are cold soaked in LN_2, crushed in a hydraulic press, and carried directly into an incinerator. In cryowashout, the SRM is mounted on an incline, and the propellant is eroded and spalled by impacting high-pressure jets of LN_2 in a spiral pattern across the inner surface of the grain. Notwithstanding limited encouragement from reported[3] data, commercial robotic systems[7] are available to spray LN_2 on unexploded ordnance (UXO) and improvised explosive devices (IEDs) but use[8] of this technology by explosive ordnance disposal (EOD) teams is limited.

High explosives are a standby in the military armamentarium and the weapon of choice among terrorists. Injury and damage from detonations of conventional chemical HEs stem primarily from the explosive shock wave pressure and impulse. Any method that can significantly reduce injury to people and damage to buildings and equipment by attenuating the intensity of explosive blasts would be beneficial in defending against and responding to attacks. A possible concurrent benefit to EOD personnel, whether used in disposal of old or obsolete ordnance or for disruption of IEDs manufactured by terrorist/extremist groups, would be to increase their chance of surviving an explosive event.

Whereas sources cited in references 1–5 cold soaked their test items to thermal equilibrium by protracted immersion in a LN_2 bath, freezing ordnance or IEDs in the field to -196°C will seldom be practical with available technology. Heroic exercises involving liquid helium or high-risk excavation or moving the device to create liquid containment are possible in principle, but when applying LN_2 under "ordinary" circumstances one can expect to attain core temperatures on the order of -100°C. To examine the possibility of useful attenuation of blast damage, this quantitative experimental evaluation of freezing common HEs with LN_2 was undertaken to look for a predictably significant, quantitative decrease in the shockwave pressure.

To include oxygen deficiency as a test parameter, two different HEs were tested. TNT is a pure chemical substance and has a relatively high oxygen deficiency, meaning that there is insufficient oxygen present in the TNT molecule to oxidize all of the carbon and hydrogen in the

compound, so oxygen from air is needed to complete the reaction ($4\ C_7H_5N_3O_6 + 21\ O_2 \rightarrow 28\ CO_2 + 10\ H_2O + 6\ N_2$). In contrast, C4 is a composite chemical mixture of the explosive RDX and a plasticizer, and the mixture has a relatively low oxygen deficiency—meaning that little ambient air is required to complete the detonation reaction ($2\ C_3H_6N_6O_6 + 3\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + 6\ N_2$) . The test temperature of –100°C was selected because it is well below the temperature at which C4 turns plastic (-70°F, –57°C), it was easy to achieve with the equipment on hand, and it is higher than the temperature of LN_2 so that the explosive charges reached this core temperature in minutes.

Incident pressure and impulse were chosen as the comparative parameters to determine what effect cooling had on the energy release of the explosive materials. The explosives were tested at ambient temperature [approximately 85°F (30°C)] and –150°F (–100ºC). Time histories of incident pressure were measured and recorded along orthogonal axes at four distances from the blast origin, which allowed comparison of both incident pressure and incident impulse. Three reference tests were performed for each chemical explosive using 1-lb charges. Three tests were conducted with C4 cooled to –150°F, and two tests were completed with TNT cooled to –150°F.

1.3 Scope

Time histories of incident pressure for TNT and C4 were tested at 85°F (30°C) and –150°F (–100ºC) at 4, 6, 10, and 20 feet from the charge, and incident pressure and impulse from the different explosive materials were compared at different temperatures. Analysis of the results showed no significant decrease in incident pressures and only a small decrease in incident impulse at the shorter distances for both TNT and C4.

2.0 Methods and Procedures

2.1 Equipment

2.1.1 Cooling Apparatus. A diagram of the equipment used to cool the explosive charges is shown in *Figure 2*. Numbers on the diagram identify system components that are described below:

(1) *Liquid nitrogen dewar*. Commercial 180-L liquid tank rated at 22 psi.

(2) *Pressure relief valve*. The pressure relief valve was integral to the delivery tubing.

(3) *Armored and insulated ¼-in stainless steel liquid nitrogen tubing*. 15 ft (Sigma Systems Corporation).

(4) *Solenoid-operated flow control valve* (120 V) (Sigma Systems Corporation).

(5) *Inner cooler*. A 1-gal styrofoam cooler with 2 in wall thickness.

(6) *Outer cooler*. A 5-gal styrofoam cooler with 2 in wall thickness.

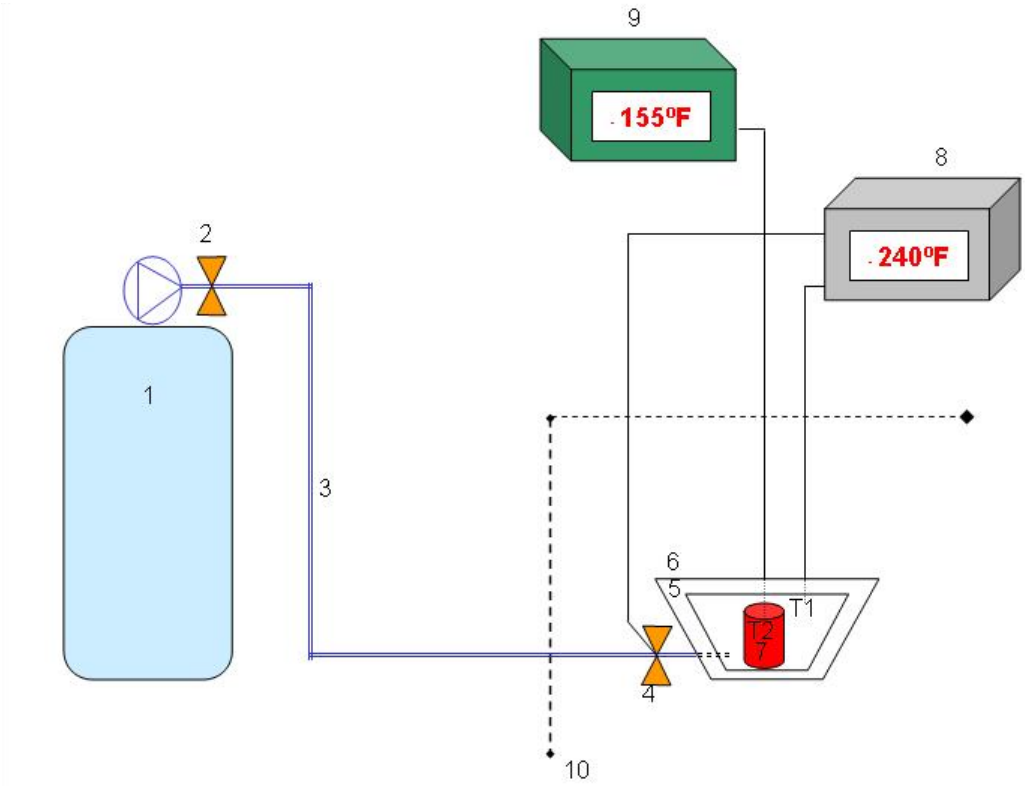

Figure 2. Equipment for Cooling the Explosive Charges**.**

(7) *Explosive charge*. One-pound charges of TNT and C4 explosive were tested. Both types of charges were initiated with RP-83 exploding bridge wire (EBW) detonators. The TNT was in pre-cast rectangular parallelepiped blocks approximately 2 x 2 x 6 in. C4 was cut from standard 1.25-lb bricks and formed into a spherical shape.

(8) *Temperature control unit and thermocouple T1*. A model C32 temperature controller was used to operate valve 4 (both from Sigma Systems Corporation). Temperature range of the control unit was –326°F to +570°F (–199°C to +299°C) and set point accuracy was ±0.2°F (±0.1°C). Thermocouple T1 measured temperature inside the inner cooler and sent a signal to the temperature controller, which compared the inner cooler temperature to a reference temperature set at the controller. Thermocouple T1 was a 0.032 in diameter type K chromel–alumel uninsulated thermocouple with a temperature range of -328°F to +2282°F (-200°C to +1250°C) and accuracy of ±2% below 32°F (0°C).

(9) *Temperature monitor and thermocouple T2*. A DP21 Series 1/8 DIN Digital Temperature Indicator (Omega Engineering, Inc.) was used to remotely monitor the internal temperature of the explosive charges as measured by thermocouple T2. Specifications for thermocouple T2 were the same as for thermocouple T1.

(10) *Safety shield*. The liquid nitrogen flow tubing passed through a hole in a pre-existing reinforced masonry wall to shield the dewar, temperature control, and monitoring equipment in case of an inadvertent explosion during the cooling process.

2.1.2 Data Collection Equipment. After the explosives were cooled to the desired temperature, the double coolers containing the explosive charges were moved to an instrumented test bed as shown in *Figure 3*. Six combination free-field and total (stagnation) pressure gauge stands and two stand alone free-field pressure gauges were used. The combination gauge mounts consisted of a single unit fitted with two pressure gauges (*Figure 4*). The lower circular disc held a pressure gauge side-on to the blast, and the upper tapered head held a pressure gauge face-on to the blast. This arrangement allowed measurement of incident free field pressure and stagnation pressure, respectively, at approximately the same distance from the blast origin. The two stand-alone free-field gauges were mounted to face side-on to the blast, similar to the mounting on the lower disc of the combination pressure gauge stands. Gauge specifications are given in *Table 1*.

Table 1. Pressure Gauge Specifications.

Model	Maximum Pressure	Accuracy
Kulite XT-190	200 psi	0.1% of full scale
	100 psi	
	25 psi	
	10 psi	

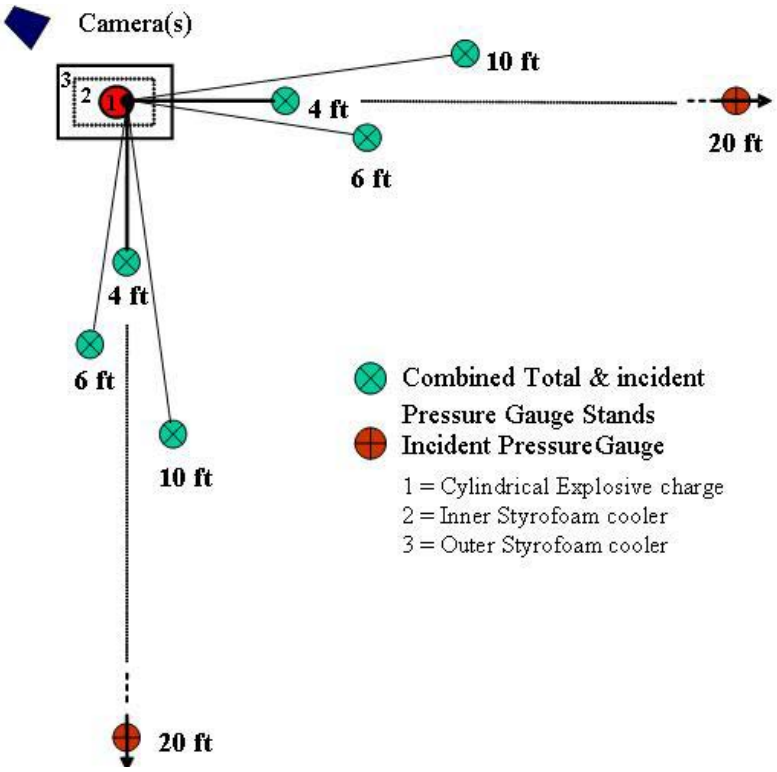

Figure 3. Experimental Test Bed.

Figure 4. Combination Pressure Gauge Stand.

A Hi-Techniques model Win600 data acquisition system was used for test data collection. The WIN 600 was triggered from an external Reynolds Industries FS-43 firing system. One Sony model DCR-PC120BT digital video camera was used to record the tests. The camera recorded standard NTSC images at a rate of 30 frames per second.

2.2 Procedure

2.2.1 RP-83 Detonator and Detonation Cord Test. Prior to the actual explosives tests, tests were conducted on an RP-83 detonator and detonation cord to confirm that the detonator and detonation cord would function normally when cooled to −150°F (−100ºC). In the first test, an RP-83 detonator was connected directly to the firing wire and then placed inside a double cooler. A small hole was cut in each of the coolers, and the LN_2 supply line was arranged to supply LN_2 to the inner cooler. A thermocouple connected to the remote temperature monitor was also placed inside the double cooler with the RP-83. The regulator valve on the nitrogen dewar was opened, the RP-83 was cooled to the set point temperature of −150°F, and the RP-83 was maintained at −150°F for 10 min to allow the internal temperature of the detonator to reach steady state. After 10 min, the LN_2 supply line was removed from the cooler, and the double cooler was carried to the test bed where the firing circuit was triggered. The RP-83 detonated normally. The second test was identical to the first except that 6 ft of detonation cord was attached to the RP-83, placed inside the double cooler, and cooled to −150°F. In this test, the RP-83 and detonation cord performed as normal.

2.2.2 Baseline Tests. Baseline tests at an ambient temperature of 85°F (30°C) were conducted with 1-lb charges of TNT and C4 to establish reference pressures. Three baseline tests were conducted for each of the explosive types. The explosive charges were placed in double coolers and then onto a test bed (*Figure 3*). Baseline tests were conducted following the same procedure as for the cooled explosives. The TNT was in 2 x 2 x 6-in pre-cast rectangular parallelepiped blocks. The C4 was cut from standard 1.25-lb bricks and formed into a spherical shape. Both types of charges were initiated with RP-83 detonators.

2.2.3 Cooled Explosive Tests. The cryogenic cooling apparatus was set up as shown in *Figure 2*, and the test bed was set up as shown in *Figure 3*. A small hole was cut in the side of each Styrofoam™ cooler for the LN_2 supply line to enter. The set point of the temperature control unit was set to regulate the inside of the double cooler at −155°F (−105°C). Thermocouples monitoring the internal temperature of the explosive charges were embedded in the explosives and connected to the remote digital temperature indicator. For C4, the thermocouple was positioned in the plastic explosive until the thermocouple junction was approximately at the center of the charge. The pre-cast TNT rectangular blocks had small holes drilled through the center of the block to insert the detonator. The thermocouple was inserted into the center hole and held in place with a pliable, mastic material that filled the hole around the thermocouple junction.

The explosive charges were placed inside a small Styrofoam™ cooler, which was then placed inside a larger cooler. The thermocouple connected to the temperature controller was placed inside the small, inner cooler along with the explosive charge, as shown in *Figure 5*. The

LN_2 supply line entered the double cooler through two small holes in the cooler walls, and lids were placed on both the inner and outer coolers. The LN_2 supply valve was opened, and the internal temperature of the explosive was monitored until a temperature of –155°F (–105°C) was reached. This occurred after a period of approximately 30 min for C4 and 50 min for TNT. Although the temperature of the explosives was maintained at -155°F during the cooling process, it was estimated that there would be a rise in temperature of approximately 5°F during transportation of the explosive from the cooling area to the test bed. Therefore, test results were recorded using -150°F.

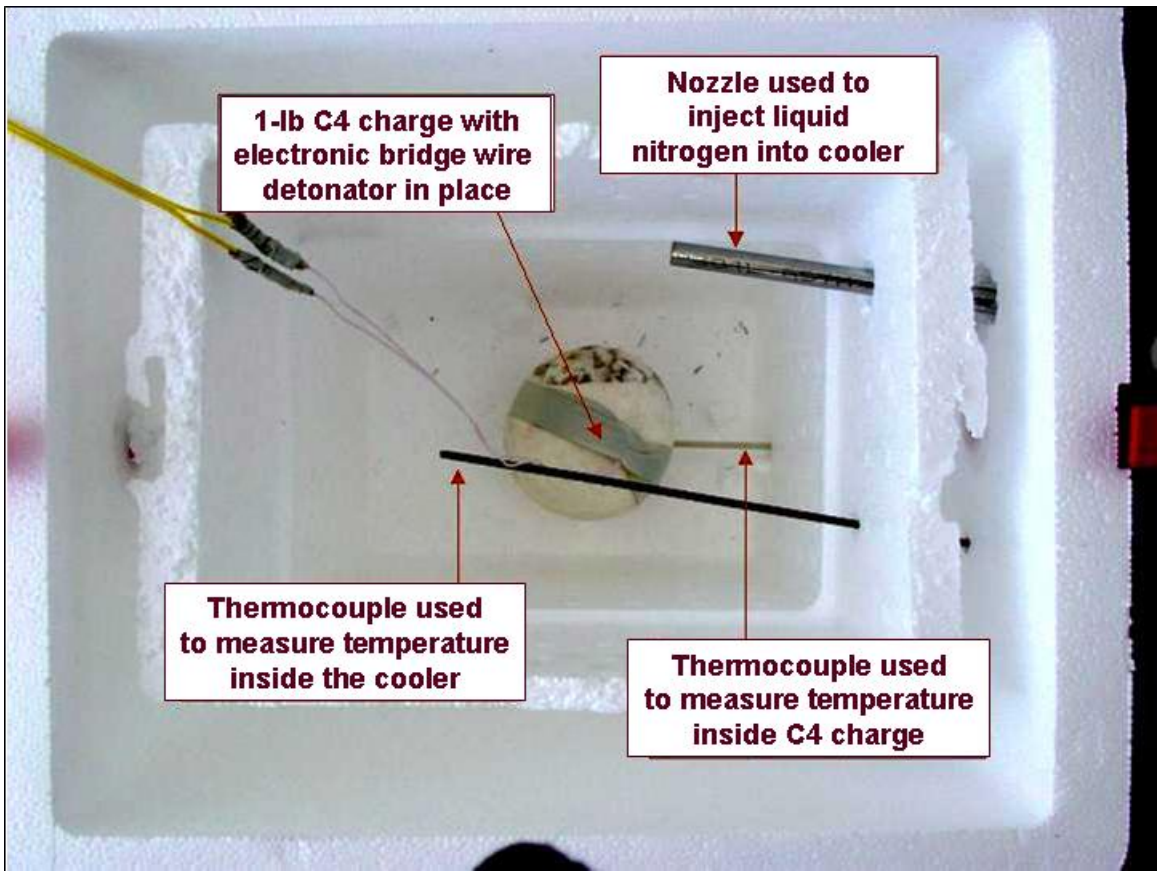

Figure 5. Placement of Explosive and Instruments in Insulated Coolers.

After the internal temperature of the explosive reached –155°F, the LN_2 supply valve was closed, the supply tubing was removed from the coolers, the thermocouple leads were cut, and the entire double cooler with explosive was moved to the test bed, a distance of about 75 ft. At the test bed, the firing line was connected to the detonator leads, and the explosive was detonated. Three tests were conducted using C4, and two tests were completed using TNT.

3.0 Results and Discussion

Results for the C4 and TNT tests are shown in *Figures 6* and *7*, respectively. At first glance, it would appear that cooling caused the incident pressure from TNT to increase and the incident pressure from C4 to decrease. However, there is no significant statistical difference in incident pressure between the shots at ambient temperature and at –150°F for both TNT and C4 at distances of 6, 10, and 20 ft.

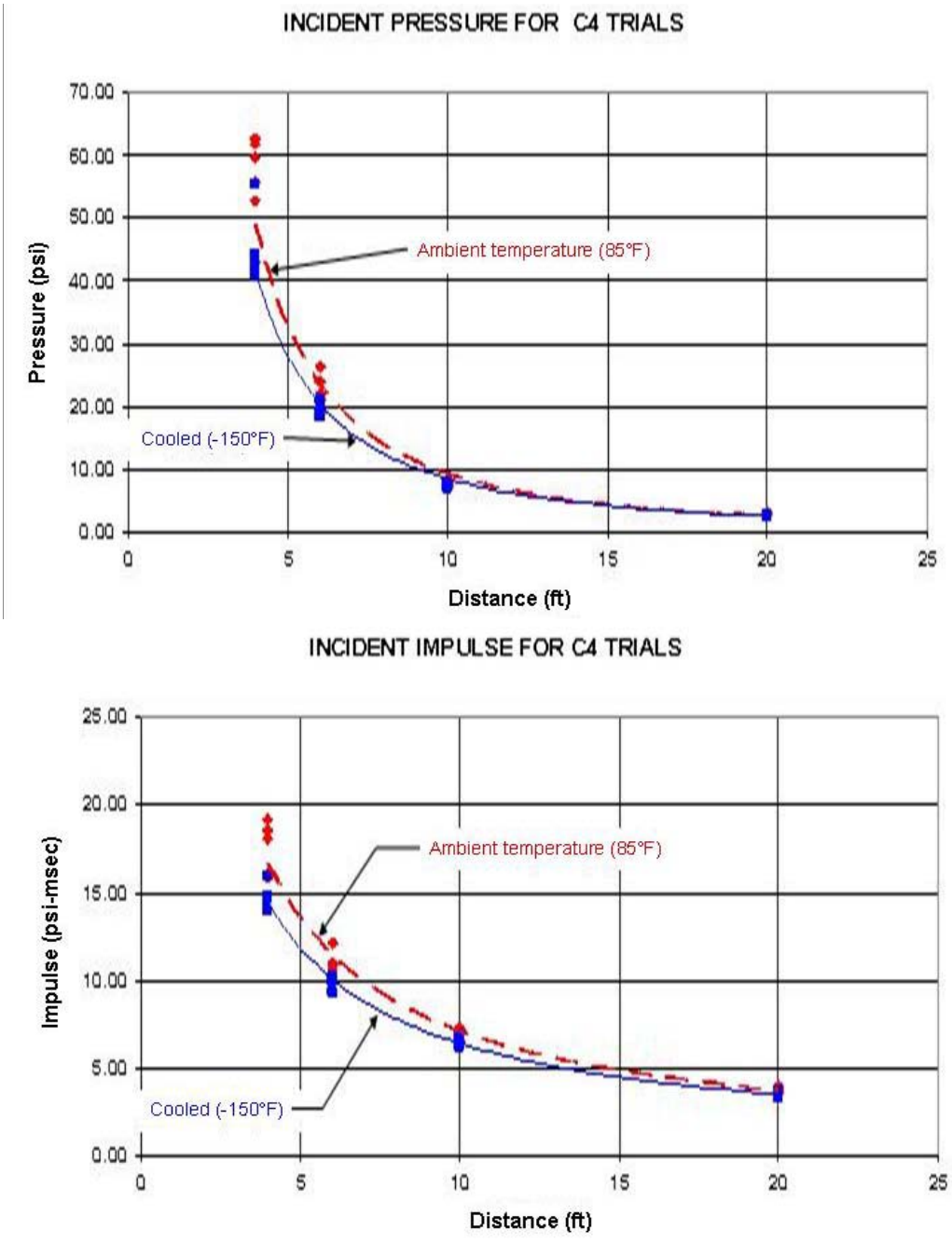

Figure 6. Incident Pressure and Impulse Graphs for C4 Tests.

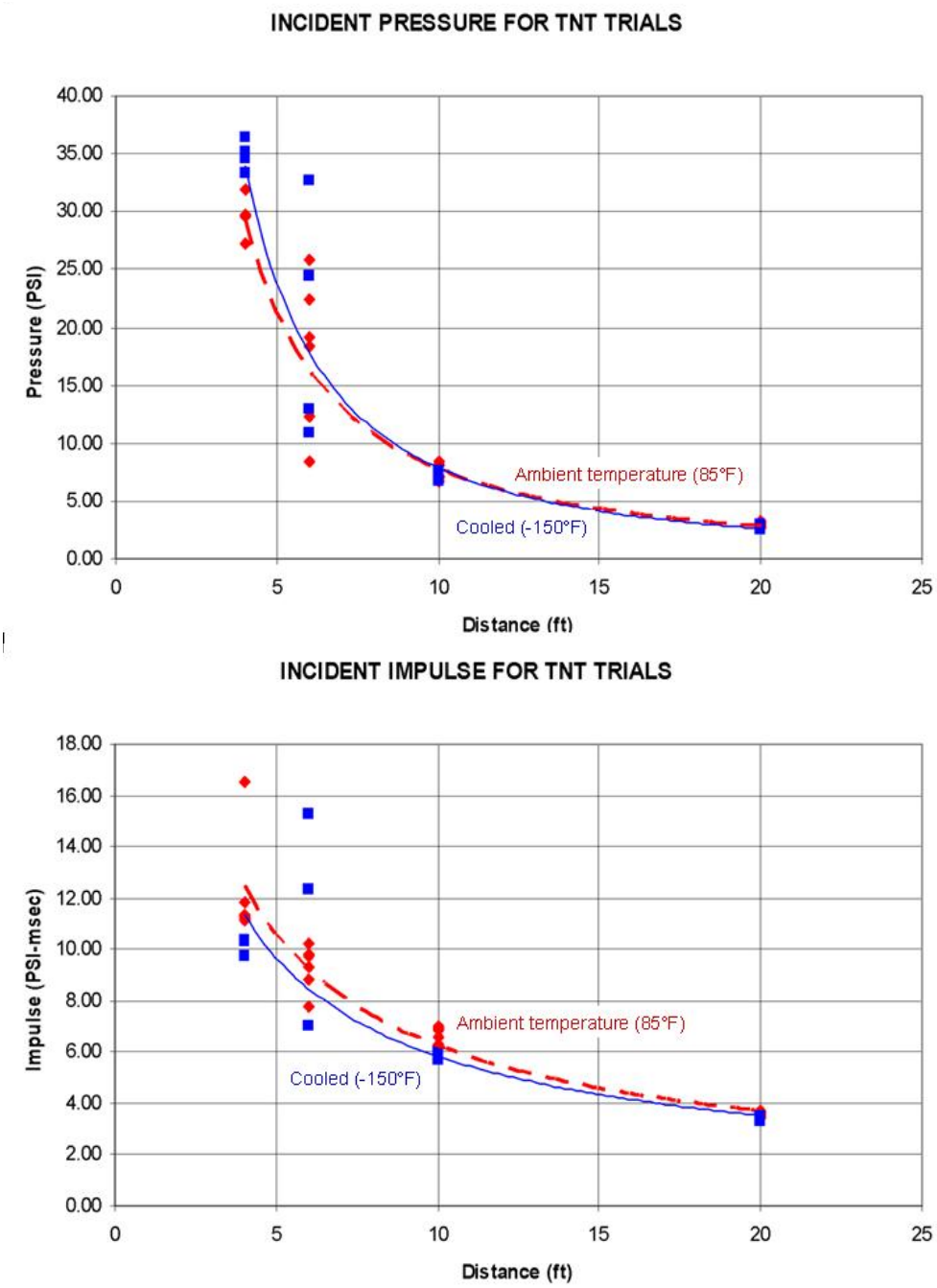

Figure 7. Incident Pressure and Impulse Graphs for TNT Tests.

Incident impulse measurements for both TNT and C4 show a more consistent trend in mitigation at all distances. Generally, data for the shots at ambient temperature and at -150°F differ by more than one standard deviation, indicating a significant statistical difference in incident impulse between the ambient and cooled explosive tests. Over the range of distances at which measurements were taken, an average 9.5% reduction in incident impulse is observed for both TNT and C4. However, the reduction in incident impulse decreases with distance from the blast origin, approaching the significant threshold 20 feet from the blast.

4.0 Conclusions

Cooling to -100°C (−150°F) did not significantly reduce the air blast overpressures from TNT or C4. The average 9.5% reduction in incident impulse observed for both TNT and C4 decreased with distance from the blast and was not sufficient to significantly reduce the potential for considerable damage and injury. We conclude that cooling to -100°C will be insufficient to reduce the damaging effects of explosive blasts.

5.0 Recommendations

Whereas expedient cooling is shown not to be useful for mitigation of blast effects, the observation of a measurable decrease in incident impulse at -100°C argues that additional testing at the boiling points of nitrogen (-320°F, -196°C) and helium (-452°F, -269°C) should be conducted in a prepared environment to determine the maximum mitigating effect possible and the approximate shape of its temperature dependence. However, because any field application of temperatures below -200°C will face such practical problems as suffocation, frostbite, and condensation of oxygen, any application to EOD will require a specialized team and dedicated equipment.

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